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ENERGY, EXERGY AND PARAMETRIC ANALYSIS OF A NEW COGENERATION SYSTEM INCLUDING THE BRAYTON AND AMMONIA–WATER RANKINE COMBINED CYCLE

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ABSTRACT

Efficient consumption of energy resources and minimizing relevant costs are both substantial issues that not only don't fade into insignificance by time but also have turned out to be essential concerns due to energy crisis and recent price rises in fuel carriers. Recently, much more efforts are made to develop modern systems do decrease the amount of energy consumption and relevant costs regarding to the problems of energy and environmental pollution. Combined Heat and Power (CHP) is one of the systems, which means, generation of two types of energy simultaneously. CHP involves concurrent thermodynamic generation of two or more forms of energy from one simple primary source. CHP has a long history of application in various industries. Applying new approaches to optimize energy consumption has been always one of the most significant issues to draw scientists' attention. The proposed configuration in this new study has not yet been provided in other studies. The current study deals with a cogeneration system for simultaneous production of electricity and heat based on an energy and exergy analysis method. The applied simulation method involves writing conservation equations of energy and mass, and pertinent relations to exergy analysis with the aid of Engineering Equation Solver program (EES) as the initial stage. The effects of design parameters including the compressor pressure ratio, input temperature of the gas turbine, organic evaporator temperature, etc., will be taken into an account as well. The results of the analysis are presented in tables and diagrams.

***KEYWORDS:** Energy, Exergy, New Cogeneration System & Parametric Analysis*

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Original Article

1. INTRODUCTION

In recent years, various studies have been carried out on the use of Brayton and Rankine cycle as well as the combined cycle for power generation. In these studies, the thermodynamic characteristics of the cycles have been considered and their performance is optimized. On the other hand, investigations on the new Brayton cycle with regeneration have been limited, which is the main motivation to conduct for this study. Sánchez-Orgaz et al., (2015) addressed Brayton gas cycle with several intermediate coolant compressor stages and several turbine stages with intermediate heating in terms of the first law. In this study, they used a solar collector and regenerating exchanger as a cycle stimulator and examined the effect of different factors on cycle performance. Anvari et al. (2016), studied the gas turbine and organic Rankine combined cycle with an intermediate heater for heat and power cogeneration in terms of energy and exergy. In this gas cycle, the temperature above the outlet of the gas turbine first enters the vapor generator and after generating the output heat of the cycle and reducing the temperature, it is used as organic Rankine cycle's stimulus. Saghafifar et al. (2016), studied Brayton and Steam Rankine combined cycle with a capacity of 50 megawatts based on energy and cost effectiveness. In this study, the heliostat collector and combustion chamber were used as a simultaneous stimulus for the Brayton cycle, and

the output hot gases from the gas turbine were used as a steam cycle stimulus. Mohammadi et al. (2017), examined a power, heat and cooling multi-generation system including the upper Brayton and the organic Rankine cycles and lower absorption refrigerator cycle thermodynamically. In the next step, a parametric analysis was performed to determine the effect of different factors on the output parameters. MohammadiKhoshkar et al (2016) studied and compared the effect of using two different types of fuel, i.e., natural gas and diesel fuel on Brayton–Rankine combined system performance in terms of energy, exergy, economic and environment. Javanshir andSarunac (2017), examined the effect of 23 dry, wet, and isentropic fuel agents on performances of ORC cycle and Brayton's ORC recovery combined cycle based on analyzing the first law of thermodynamic (thermal efficiency and net output power). M.E. Mondejar et al. (2018), studied the Rankine organic cycle to be used in maritime transportation. The obtained results showed that the Rankine cycle may reduce fuel consumption by 10–15% through recovering heat from internal exhausts.

Considering the previous efforts in literature, it seems that using the proposed recovery gas turbine cycle can increase energy efficiency and the system exergy, and in turn, decrease fossil fuel consumption and the resulted pollution because it consumes less fuel compared to conventional gas turbine cycles. Moreover, all previous analyses on the new recovery cycle have been carried out from energy perspective, thus the shortage of studies to examine the environmental impacts and simulation of emissions necessitate further researches with a more comprehensive focus on exergy performance and environmental aspects. The present study tries to propose the combined system for cogeneration of power and heat including the new Brayton's recover cycle, steam generation, and Rankine organic cycle with a two-agent water–ammonia fluid, and to examine it from energy, exergy, and parametric analysis perspectives. It will be possible to evaluate resultant increase in the cycle efficiency.

1.1 Equation of Energy Balance

Equation of energy balance in a control volume involves all input and output energy. The first law of thermodynamic which is also called as energy conservation law is defined as below (Ahmadi et al., 2011; Ahmadi et al., 2013; Bejanand Tsatsaronis, 1996; Roy et al., 2011):

$$\dot{Q} - \dot{W} + \sum_i \dot{m}_i \left(h_i + \frac{{v_i}^2}{2} + gZ_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{{v_e}^2}{2} + gZ_e\right) = \frac{dE_{cv}}{dt} \tag{1}$$

1.2 Exergy Destruction

Calculation of exergy destruction is usually the main purpose of exergy analysis in a system because it is accountable for the loss of sources in chemical–thermal systems. Thus, certain methods are usually used to reduce this loss in analysis of exergy. Exergy equilibrium may be used to determine the type and amount of energy source loss in a single component. It also presents the solutions to more efficient use of fuel sources. Exergy equilibrium for a system in stable state is written as below (Abusoglu and Kanoglu, 2009;Dincer, 2012; Sayyaadi and Aminian, 2010; Hamidi, 2008):

$$\dot{Ex}_i + \dot{Ex}_Q = \dot{Ex}_e + \dot{Ex}_w + \dot{Ex}_D \tag{2}$$

where $\dot{Ex}_e$and $\dot{Ex}_i$ refer to exergy output and input flow rate from and into the system respectively, $\dot{Ex}_Q$ is rate of exergy corresponding to heat transfer (for positive input heat), $\dot{Ex}_w$ is work transfer rate (for the accomplished work by positive system), and $\dot{Ex}_D$ is the rate of exergy destruction (Dincer, 2012; Hosseini et al., 2017; Sayyaadi and Aminian, 2010).

1.3 Efficiency of Exergy (Second Law Efficiency)

Defining exergy ratios appear to be useful to keep focus on the exergy distribution across a process. Exergy efficiency is a parameter that is used for examining the thermodynamic performance, and also provides a realistic evaluation of efficiency in an energy system from thermodynamic perspective (Ganjehkaviri et al., 2014; Saghafifar and Gadalla, 2016).

$$\eta_{ex} = \frac{\dot{Ex}_P}{\dot{Ex}_F} = 1 - \frac{\dot{Ex}_D + \dot{Ex}_L}{\dot{Ex}_F} \tag{3}$$

2. EXAMINING THE PERFORMANCE OF THE NEW COMBINED COGENERATION SYSTEM

Figure 1 shows the schematic diagram of the combined Brayton gas–steam generator and Rankine water–ammonia organic cycle for the purpose of cogenerating power and heat driven by the fossil fuel. As can be seen in Figure 1, the upper Brayton cycle consists of four components, namely, compressor, recovery converter, combustion chamber, and gas turbine 1. In this cycle, air with ambient pressure and temperature enters into the compressor. Then it travels to the combustion chamber once the pressure and temperature increase by passing through recovery converter. Once the fossil fuel has been combusted, mixture of gases with high pressure and temperature enters into the gas turbine 1 to generate power. A portion of heat from the hot flow at the gas turbine 1 output is transferred to the compressor output leading to reduce fossil fuel consuming and adverse environmental impacts. At the gas turbine 1 output, the mixture of outgoing gases is expanded to atmospheric high pressure. In this mode, turbine 1 pressure ratio is adjusted in a way that is able to provide required work for Brayton cycle compressor 1and whole output from turbine 2 and the lower Rnakine cycle. In the gas turbine 2, outgoing gases expand up to atmospheric pressure so that they can supply a major portion of the work to be done by the cycle output. Hot gases leaving the gas turbine 2 lose their temperature initially in the steam generator to produce steam and then in the evaporator organic cycle with water–ammonia fluid. Rnakine organic cycle is also a simple four-element cycle that produces saturated water–ammonia steam and enters into the turbine. Organic cycle output is produced in the power turbine, then the output fluid converts to saturated liquid in the condenser. Ultimately, the pump raises fluid pressure to maximum pressure of the organic cycle, and the cycle is completed.

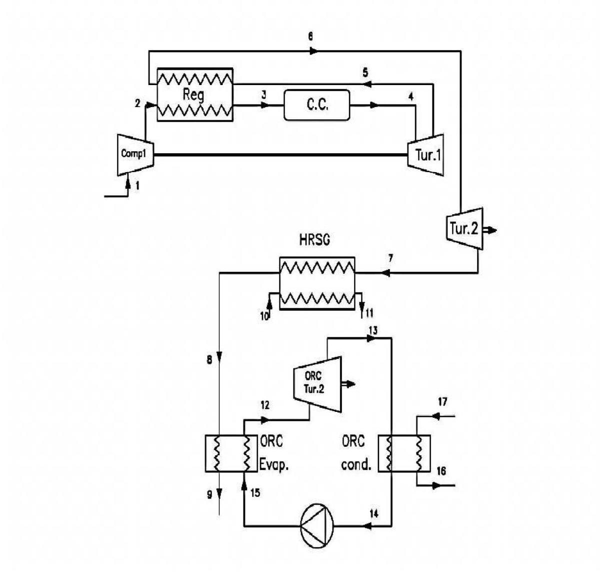

Figure 1: Schematic Diagram of the Combined System for Cogeneration of Heat and Power.

3. EXERGY ANALYSIS ON COMBINED COGENERATION SYSTEM

Table 1: Definition of Product and Fuel Exergy in Various Components of Combined System

Component	Fuel Exergy	Product Exergy
Compressor 1	$\dot{W}_{com}$	$\dot{Ex}_2 - \dot{Ex}_1$
Recovery Converter	$\dot{Ex}_5 - \dot{Ex}_6$	$\dot{Ex}_3 - \dot{Ex}_2$
Combustion Chamber	$\dot{Ex}_3 + \dot{Ex}_{fuel}$	$\dot{Ex}_4$
Turbine 1	$\dot{Ex}_4 - \dot{Ex}_5$	$\dot{W}_{gas,tur,1}$
Turbine 2	$\dot{Ex}_6 - \dot{Ex}_7$	$\dot{W}_{gas,tur,2}$
Steam Generator	$\dot{Ex}_7 - \dot{Ex}_8$	$\dot{Ex}_{11} - \dot{Ex}_{10}$
Organic Evaporator	$\dot{Ex}_8 - \dot{Ex}_9$	$\dot{Ex}_{12} - \dot{Ex}_{15}$
Organic Turbine	$\dot{Ex}_{12} - \dot{Ex}_{13}$	$\dot{W}_{of,tur}$
Organic Condenser	$\dot{Ex}_{13} - \dot{Ex}_{14}$	$\dot{Ex}_{17} - \dot{Ex}_{16}$
Organic Pump	$\dot{W}_{of,p}$	$\dot{Ex}_{15} - \dot{Ex}_{14}$

4. OUTPUT PARAMETERS ARE LIKE FOLLOWING RELATIONS

$$\dot{W}_{\text{net}} = \dot{W}_{\text{gas,tur,2}} + \dot{W}_{\text{of,tur}} - \dot{W}_{\text{of,p}} \quad (4)$$

$$\eta_{\text{en,net}} = \frac{\dot{W}_{net} + \dot{Q}_{HRSG}}{\dot{m}_{fuel}\ LHV} \quad (5)$$

$$\eta_{\text{ex,net}} = \frac{\dot{W}_{net} + (\dot{Ex}_{11} - \dot{Ex}_{10})}{\dot{Ex}_{fuel}} \quad (6)$$

5. CONCLUSIONS

EES program is used to simulate all the equations of energy and mass conservation, relations of irreversibility, and relations associated with exergy analysis for various components of the combined system as well. For the purposes of verifying simulation results of this study, irreversibility values of various components of the simulated Brayton gas cycle have been compared to the reference Brayton cycle (Goodarzi, 2016) without solar collector, and also the total similar parameters as stated in order to verify values of temperature, pressure, flow rate, enthalpy, and entropy . As can be seen, the obtained results are desirably consistent with the reference results.

5.1 Conclusions of Basic State

Using input items, equations of mass and energy balance, and relations associated with exergy, outputs related to temperature, pressure, and other items relevant to various components of the combined system are obtained as presented in Table 2. As can be seen, the sum of physical and chemical exergy of input gases mixture entering turbine 1 accounts for the highest range of exergy, which seems reasonable regarding to the high temperature and pressure at this point.

Table 3 presents the output values related to the energy rate and exergy of various components of the cycle, and exergy efficiency of various components of the combined cycle as well. As can be seen, the largest amount of exergy destruction with a large distance from other components occurs within the combustion chamber, which is considerable as compared to remaining components. Recovery converter and compressor come in second in terms of exergy destruction. Furthermore, the highest exergy efficiency is observable for turbine and compressor in gas cycle, while organic condenser shows the lowest range of exergy efficiency. In the combined cycle for power generation in basic input state, total work is 71619 kilowatt, total irreversibility is 103054 kilowatt, total energy efficiency is 56.2, and total exergy efficiency is 43.3 percent.

Table 2: Output Values of Temperature, Pressure, etc. Related to Various Components of the Combined System

Sl. No.	Material	$T(°C)$	$P\ (kPa)$	$\dot{m}(\frac{kg}{s})$	$h(\frac{kj}{kg})$	$s(\frac{kj}{kg.j})$	$\dot{E}x(kW)$
1	Air	25	101.3	400	-163.8	6.943	0
2	Air	338.2	101.3	400	161.8	7.02	121056
3	Air	750	962.4	400	624	7.611	235516
4	Gas Mixture	1100	914.2	403.7	565.9	8.102	373669
5	Gas Mixture	838.5	318	403.7	243.3	8.15	237599
6	Gas Mixture	448	308.4	403.7	-214.6	7.652	112541
7	Gas Mixture	302.7	112.2	403.7	-375.6	7.699	41973
8	Gas Mixture	225.4	106.6	403.7	-458.8	7.559	25245
9	Gas Mixture	86.1	101.3	403.7	-605.5	7.229	5700
10	Water	25	3500	12.46	108	0.366	42.45
11	Water	242.6	3500	12.46	2803	6.124	12240
12	Water-ammonia	192.4	4000	29.64	1954	5.308	433081
13	Water-ammonia	124.8	800	29.64	1725	5.452	425007
14	Water-ammonia	31.2	800	29.64	-49.97	0.356	417414
15	Water-ammonia	31.86	4000	29.64	-44.56	0.359	417545
16	Water	25	101.3	1257	104.8	0.366	0
17	Water	35	101.3	1257	146.7	0.504	888.9

Table 3: Energy and Exergy Results of the Combined System

Component	$\dot{Q}$ or $\dot{W}(kW)$	$\dot{E}x_f(kW)$	$\dot{E}x_p(kW)$	$\dot{E}x_D(kW)$	$\eta_{ex}(\%)$
Air Compressor 1	130271	130271	121056	9215	92.9
Recovery Converter	184880	125058	114460	10599	91.5
Combustion Chamber	-	428976	373669	55307	87.1
Gas Turbine 1	130271	136070	130271	5799	95.7
Gas Turbine 2	64975	70567	64975	5592	92
Steam Generator	33581	16729	12197	4532	72.9
Organic Evaporator	59243	19544	15536	4008	79.4
Organic Turbine	6805	8074	6805	1270	84.2
Organic Condenser	52599	7593	888.9	6704	11.7
Organic Pump	160.5	160.5	131.7	28.83	82

5.2 Parametric Analysis Results

This section examines the effects of changes in Brayton compressor pressure ratio, turbine input temperature, etc. on system performance in terms of energy and exergy. As can be seen in figure 2, increase in pressure ration compressor leads to increase in total output work, increase in total exergy efficiency, and decrease in total energy efficiency. In this case, increase in pressure ratio with keeping fuel, gas mixture of combustion chamber, and air flow rate constant, will raise enthalpy difference in gas turbine 2 and its work. On the other hand, energy conservation relation in organic evaporator leads to increase in organic cycle which in turn increases organic cycle work. Total work also increases when its terms rise. As can be seen in Figure 2, increase in compressor pressure ratio leads to decrease in output exergy at steam generator, for which a clear and strong descending trend of output energy is observable. This reduces energy efficiency in spite of increase in total output work. However, in case of exergy efficiency, increase in total work has a dominant effect which increases efficiency. Similarly, figure 3 shows that increase in pressure ratio leads to a considerable decrease in irreversibility within Brayton cycle recovery converter, so turbines 1 and 2 decrease total irreversibility of the combined system in spite of irreversibility rise in compressor. Variations of exergy destruction within combustion chamber are negligible and not presented in the figure.

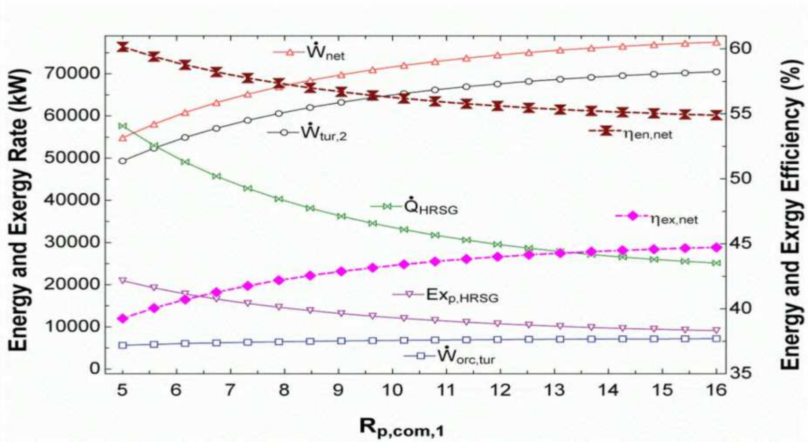

Figure 2: Effect of Changes in Brayton Compressor Pressure Rate on Energy and Exergy Performance.

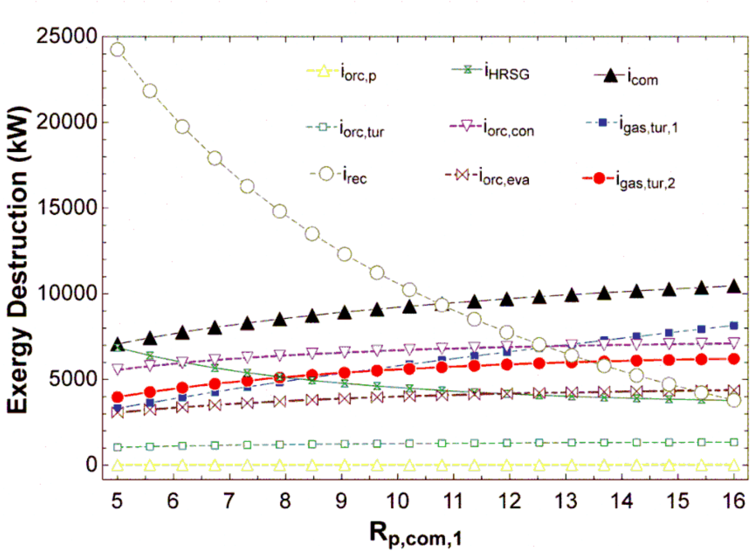

Figure 3: Effect of Changes in Brayton Compressor Pressure Rate on Irreversibility of Various Components.

Figures 4 and 5 show the effects changes in turbine 1 input temperature on energy and exergy performance of the combined system, on irreversibility of various components, respectively. As can be seen in the figure, increase in turbine 1 input temperature increases the fuel flow rate, gas flow rate, and enthalpy difference of turbine 2 which will experience work rise. On the other hand, energy conservation relations at steam generator and organic evaporator lead to increase in the rate of generated heat at steam generator and decrease in organic cycle flow rate, respectively. Decrease in organic cycle flow rate increase its work. In case of total work, increase in gas turbine work is more effective which increases the total work. Moreover, increase in both total work and rates of energy and exergy of the steam generator, leads to increase in energy and exergy efficiency of the combined system. As can be seen in figure 5, increase in irreversibility within combustion chamber and recovery converter will raise total irreversibility of the combined system.

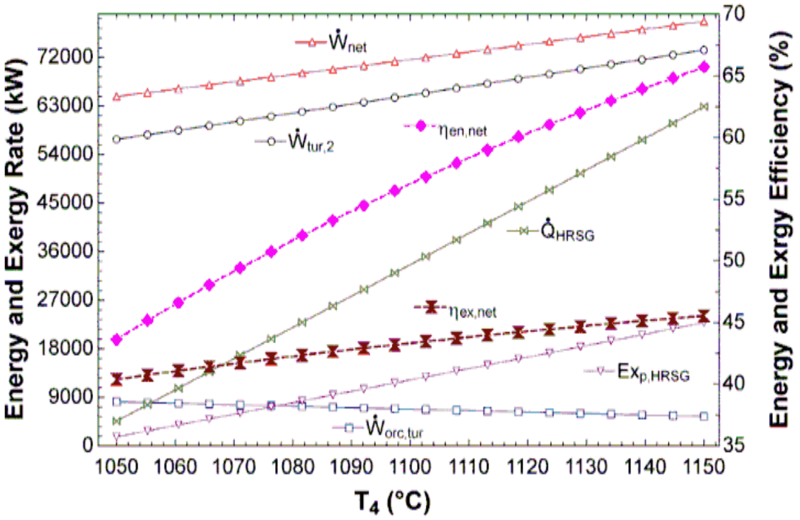

Figure 4: Effect of Changes in Turbine 1 Input Temperature on Energy and Exergy Performance.

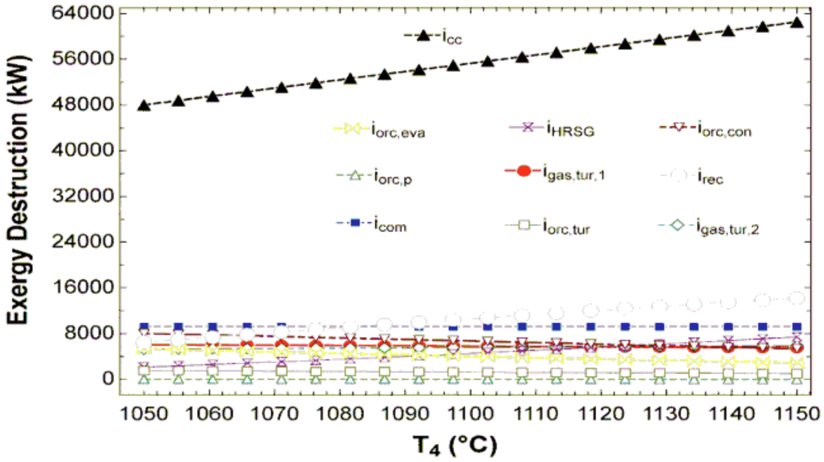

Figure 5: Effect of Changes in Turbine 1 Input Temperature on Irreversibility of Various Components.

Figures 6 and 7 show effects of changes in maximum pressure of organic Rankine cycle on energy and exergy performance of the combined system on irreversibility of various components. As can be seen in Figure 6, increase in maximum pressure leads to increase in output work and efficiency. Increase in maximum pressure of organic Rankine cycle results in reducing organic cycle flow rate through writing energy conservation relation. On the other hand, increase in maximum pressure leads to higher enthalpy difference at organic turbine, which increases the organic cycle output work and total work with keeping other items constant in spite of decrease in flow rate. As can be seen in Figure 7, increase in maximum pressure will reduce the irreversibility in condenser and organic cycle evaporator, which reduce the total irreversibility, which ultimately results in lower total irreversibility in spite of increasing irreversibility in organic turbine and keeping irreversibility constant in other components.

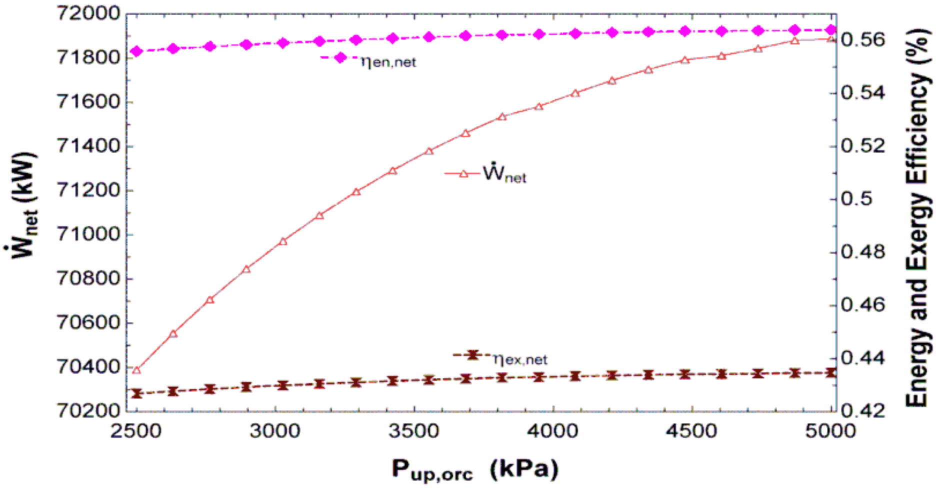

Figure 6: Effects of Changes in Maximum Pressure of Organic Rankine Cycle on Exergy and Energy Performance.

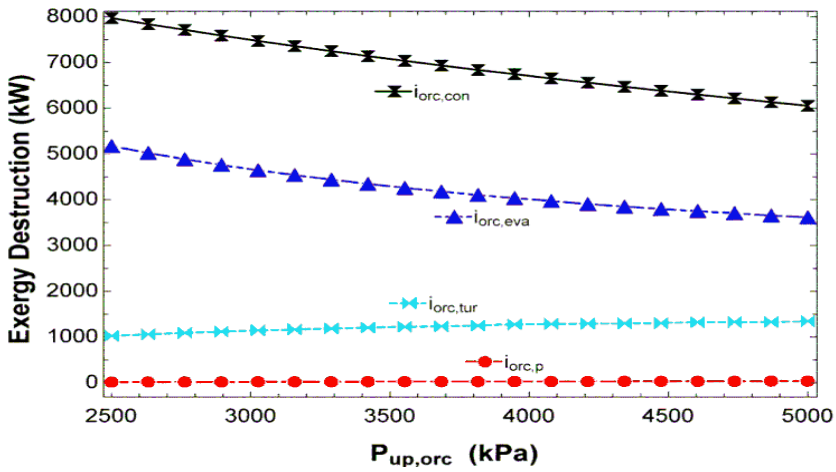

Figure 7: Effects of Changes in Maximum Pressure of Organic Rankine Cycle on Irreversibility.

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